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DISCRIMINATING UNDERGROUND EXPLOSIONS FROM EARTHQUAKES USING SEISMIC CODA WAVES

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JANUARY, 1994

STUDY ON THE DISCRIMINATION OF EXPLOSIONS AND EARTHQUAKES AT REGIONAL DISTANCE BY USING CODA Q_c^{-1} METHOD

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OBJECTIVE

The objective of this study is to discriminate the explosions and earthquakes at regional distance by using the coda wave method. In an earlier study, Su and Aki (1991) found a significant difference in coda attenuation, Q_c^{-1}, for quarry blasts and earthquakes at frequencies of 1.5 and 3 Hz for lapse time less than 30 seconds (see Fig. 1), and they suggested that such a significant difference in Q_c^{-1} may be attributed to the seismic surface wave's contributions. To interpret the observed seismic coda waves we need to consider the seismic surface wave scattering processes. Wu (1985) and Zeng et al. (1991, 1993) have shown that the energy transfer theory can successfully describe the seismic body waves scattering processes in a random scattering and absorption full-space medium. In this study, we shall first use the energy transfer equations to study the seismic surface waves scattering processes and the surface wave with body waves scattering processes in order to interpret the Su and Aki's observed results. We shall then extend this method to study the explosions and earthquakes at regional distance.

RESEARCH ACCOMPLISHED

1. Energy transfer theory for Rayleigh wave

In this section, we shall consider a simple case in which the background medium is a homogeneous half-space. The only surface wave in this case is the Rayleigh wave. In this section, we neglect the conversions between the body waves and the Rayleigh wave, and consider only energy distribution of Rayleigh wave in an absorptive and scattering medium. The energy density at $\mathbf{x}$, and ω, due to a point steady source at $\mathbf{x}_s$ can be written as

$$E^R(\mathbf{x},\omega) = G(\mathbf{x},\mathbf{x}_s)\exp[-\eta^R\,|\mathbf{r}-\mathbf{r}_s|]E_0^R(\mathbf{x}_s,\omega) + \sum_j \sigma(\mathbf{x}_j)G(\mathbf{x},\mathbf{x}_s)\exp[-\eta^R\,|\mathbf{r}-\mathbf{r}_j|]E^R(\mathbf{x}_j,\omega), \quad (1)$$

where, $\mathbf{r} = \mathbf{x}-\hat{\mathbf{e}}_z(\mathbf{x}\cdot\hat{\mathbf{e}}_z)$ is a horizontal vector, and η^R is the attenuation coefficient that includes the intrinsic (η_i^R) and scattering attenuation (η_s^R), i.e., $\eta^R = \eta_i^R + \eta_s^R$. In eq.(1), $E^R(\mathbf{x},\omega)$ is the seismic energy per unit volume carried by Rayleigh wave at point $\mathbf{x}$ and frequency ω. The first term in the right-hand-side of (1) represents the direct Rayleigh wave energy radiated from source, and the second term in the right-hand-side of (1) describes the total scattering energy from all scatterers ($\mathbf{x}_j$). Where σ is the scattering cross-section, $G(\mathbf{x},\mathbf{x}_j)$ and $\exp[-\eta^R|\mathbf{r}-\mathbf{r}_j|]$ describes the geometrical spreading and attenuation, respectively. It should be noted that the attenuation is caused only by the horizontal propagation, since we only consider surface wave in this section.

For weak scattering cases, the scattering cross-section σ can be analytically derived by using Born approximation (Aki and Richards, 1980). Here, for simplicity, we assume that σ is a constant. The geometrical spreading function $G(\mathbf{x},\mathbf{x}')$, however, can be determined by the consideration of energy conservation.

Geometrical Spreading Function of Rayleigh Wave:

The direct Rayleigh wave (Rayleigh wave in the background medium) has the following form (Aki and Richards, 1980),

$$U^R(\mathbf{x},\omega) = \frac{\mathbf{P}_R(\mathbf{x})[\mathbf{P}_R(\mathbf{x}_s)\bullet\mathbf{F}(\mathbf{x}_s)]}{8(c_R)^2 I_1\sqrt{(\pi/2)k_R|\mathbf{r}-\mathbf{r}_s|}}\exp\{i[k_R|\mathbf{r}-\mathbf{r}_s|+\pi/4]\}. \tag{2}$$

Where,

$$\mathbf{P}_R(\mathbf{x}) = r_1(z,\omega)\,\hat{\mathbf{e}}_r + ir_2(z,\omega)\,\hat{\mathbf{e}}_z\,, \tag{2a}$$

with $\hat{\mathbf{e}}_r = (\mathbf{r}-\mathbf{r}_s)/|\mathbf{r}-\mathbf{r}_s|$. The corresponding energy density is

$$E_0^R(\mathbf{x},\omega) = \frac{1}{2}\rho\omega^2|U^R(\mathbf{x},\omega)|^2 = \frac{\rho\omega^2}{[8(c_R)^2 I_1]^2\pi k_R}\frac{|\mathbf{P}_R(z)|^2}{|\mathbf{r}-\mathbf{r}_s|}|\mathbf{P}_R(\mathbf{x}_s)\bullet\mathbf{F}(\mathbf{x}_s)|^2\,. \tag{3}$$

For steady state, the energy rate should be a constant for any closed-surface that encloses the source, namely,

$$\oint_S \{E_0^R(\mathbf{x},\omega)\mathbf{v}_R\}\bullet\hat{\mathbf{s}}\,dS = \text{constant}, \qquad \text{for } \mathbf{x}_s \text{ inside } S. \tag{4}$$

Where, $\hat{\mathbf{s}}$ is the normal vector of the surface element dS, and $\mathbf{v}_R$ is the velocity vector of the Rayleigh wave. Since the surface wave propagates along the horizontal direction, we consider a cylindrical surface that leads to a simple surface integration,

$$\oint_S \{E_0^R(\mathbf{x},\omega)\mathbf{v}_R\}\bullet\hat{\mathbf{s}}\,dS = \int_0^{+\infty}dz\int_0^{2\pi}R\,d\theta\,E_0^R(\mathbf{x},\omega)v_R\,.$$

Where, $R = |\mathbf{r}-\mathbf{r}_s|$. Substituting (3) in (4), we find

$$\begin{aligned}\varepsilon_0^R(\mathbf{x}_s) &= \frac{1}{v_R}\oint_S \{E_0^R(\mathbf{x},\omega)\mathbf{v}_R\}\bullet\hat{\mathbf{s}}\,dS = \frac{2\omega^2\rho}{k_R}\int_0^{\infty}|\mathbf{P}_R(z)|^2dz\,|\mathbf{P}_R(\mathbf{x}_s)\bullet\mathbf{F}(\mathbf{x}_s)|^2 \\ &= \frac{\omega^2}{8(c_R)^4 I_1 k_R}|\mathbf{F}(\mathbf{x}_s)|^2\{|r_1(z_s)n_r|^2 + |r_2(z_s)n_z|^2\}\;.\end{aligned} \tag{5}$$

Using the above result, eq. (3) can be rewritten as

$$E_0^R(\mathbf{x},\omega) = \frac{g_R(z,\omega)}{2\pi|\mathbf{r}-\mathbf{r}_s|}\,\varepsilon_0^R(\mathbf{x}_s). \tag{6}$$

Where,

$$g_R(z,\omega) = \frac{|P_R(z)|^2}{\int_0^{+\infty}|P_R(z')|^2dz'} = \frac{[r_1(z,\omega)^2 + r_2(z,\omega)^2]}{\int_0^{+\infty}[r_1(z',\omega)^2 + r_2(z',\omega)^2]dz'}\;. \tag{6a}$$

Thus, we obtain the geometrical spreading function of Rayleigh wave energy propagation as

$$G(\mathbf{x},\mathbf{x}') = \frac{g_R(z,\omega)}{2\pi|\mathbf{r}-\mathbf{r}'|}. \tag{7}$$

From equation(6a), we can verify the following identity,

$$\int_0^{+\infty} g_R(z,\omega)dz = 1\;. \tag{7a}$$

Integral equation of scattering Rayleigh wave in random medium:

We are now ready to set up the basic integral equation for Rayleigh wave scattering in random medium. Substituting eq.(7) in (1), and assuming that the random scatterers are uniformly distributed and can be described by a continuous distribution n_o(density of scatterers), we obtain the following integral equation,

$$E^R(\mathbf{x},\omega) = \frac{g_R(z,\omega)e^{-\eta^R|\mathbf{r}-\mathbf{r}_s|}}{2\pi|\mathbf{r}-\mathbf{r}_s|}\,\varepsilon_0^R(\mathbf{x},\omega) + \int_V \eta_s^R\,\frac{g_R(z,\omega)}{2\pi|\mathbf{r}-\mathbf{r}'|}\,e^{-\eta^R|\mathbf{r}-\mathbf{r}'|}E^R(\mathbf{x},\omega)dV(\mathbf{x}')\;. \tag{8}$$

Where, $\eta_s^R = n_o\sigma$. Eq.(8) is similar to the energy transfer equation for body wave (Wu, 1985; Zeng et al., 1991), but with different geometrical spreading functions and the attenuation factors that are due to the characterizations of surface wave propagation. The dependence on $|\mathbf{r}-\mathbf{r}'|$ indicates the horizontal propagation property of the surface wave, whereas, the $g_R(z,\omega)$ expresses the depth distribution of surface wave energy. Integral equation (8) can be solved by using spatial domain Fourier transform method. First, we note that equation (8) can be rewritten as

$$E^R(\mathbf{x},\omega) = g_R(z,\omega)E_2^R(\mathbf{r},\omega). \tag{9}$$

Inserting equation (9) into (8) and using the identity (7a), we obtain

$$E_2^R(\mathbf{r},\omega) = \frac{e^{-\eta^R|\mathbf{r}-\mathbf{r}_s|}}{2\pi|\mathbf{r}-\mathbf{r}_s|}\,\varepsilon_0^R(\mathbf{x}_s,\omega) + \int_\Sigma \eta_s^R\,\frac{e^{-\eta^R|\mathbf{r}-\mathbf{r}'|}}{2\pi|\mathbf{r}-\mathbf{r}'|}\,E_2^R(\mathbf{r}',\omega)\,d\Sigma(\mathbf{r}'). \tag{10}$$

Where, $\Sigma(\mathbf{r}) = \{(x,y)|-\infty<x<+\infty, -\infty<y<+\infty\}$. The corresponding Fourier transform is

$$\widetilde{E}_2^R(\mathbf{k},\omega) = \widetilde{G}_2^R(\mathbf{k})\varepsilon_0^R(\mathbf{x}_s,\omega) + \eta_s^R\widetilde{G}_2^R(\mathbf{k})\widetilde{E}_2^R(\mathbf{k},\omega). \tag{11}$$

Where, we assumed $\mathbf{r}_s = 0$, and $\widetilde{G}_2^R(\mathbf{k},\omega)$ is given by

$$\widetilde{G}_2^R(\mathbf{k},\omega) = \iint_{-\infty}^{+\infty} dxdy\,\frac{e^{-\eta^R r}}{2\pi r}\exp(i\mathbf{k}\bullet\mathbf{r}) = \int_0^{+\infty} J_0(kr)e^{-\eta^R r}dr = \frac{1}{\sqrt{k^2 + (\eta^R)^2}}. \tag{11a}$$

Substituting this result in eq.(11), then taking the inverse Fourier transform over $\mathbf{k}$, we finally obtain

$$E^R(\mathbf{x},\omega) = g_R(z,\omega)P_R(r,\eta^R,\eta_s^R)\,\varepsilon_0^R(\mathbf{x}_s,\omega). \tag{12}$$

Where $P_R(r,\eta^R,\eta_s^R)$ is the inverse Fourier transform of $\widetilde{G}_2^R(\mathbf{k},\omega)$,

$$P_R(r,\eta^R,\eta_s^R) = \frac{1}{2\pi}\int_0^{+\infty} J_0(kr)\frac{kdk}{\sqrt{k^2 + (\eta^R)^2} - \eta_s^R}. \tag{12a}$$

Solution (12) has a clear physical meaning. The term $\varepsilon_0^R(\mathbf{x}_s,\omega)$, as defined earlier, contains the seismic source information. Function $g_R(z,\omega)$ represents the depth dependence of Rayleigh wave energy, whereas the function $P_R(r,\eta^R,\eta_s^R)$ describes the propagation and attenuation processes of the Rayleigh wave energy. $P_R(r,\eta^R,\eta_s^R)$ can be obtained by evaluating integral (12a). For a pure absorption medium (η_s^R=0), we find $P_R(r,\eta^R,0) = e^{-\eta^R r}/2\pi r$. This is consistent with our direct Rayleigh wave (solution in background medium). For general absorption and scattering media, we can numerically evaluate the propagation and attenuation function $P_R(r,\eta^R,\eta_s^R)$.

It is noted that equation (8) describes a stationary energy transfer process, i.e., $E^R(\mathbf{x},\omega)$ represents the amplitude of the spectrum of scattered Rayleigh wave. To obtain the time-history of the scattered Rayleigh energy for a given frequency w and the observational point $\mathbf{x}$, we introduce a time-delay phase factor of "$\exp(-i\Omega|\mathbf{r}-\mathbf{r}'|/c_R)$", then take inverse Fourier transform over frequency Ω. During the inverse Fourier transformation, the frequency ω is kept as a constant which is defined as center frequency. Thus we can obtain the time-history of scattered energy for a given center frequency ω. Fig. 2 shows the energy distributions for the case of η_i^R=0.01, η_s^R=0.02 and ω=1Hz. As we expected the scattered energy arrived at time of $t=|\mathbf{r}-\mathbf{r}_s|/c_R$.

2. Energy transfer theory for S and Rayleigh waves' scattering processes

In the preceding section, we have considered only the scattering processes of Rayleigh wave, and neglected the body waves' conversions. In this section, we shall consider the coupling

effect of body waves with surface wave. For simplicity, we consider only the coupling process between the S wave and Rayleigh wave. The energy transfer equation described such an coupled scattering process can be written as follows,

$$E^R(\mathbf{x},\omega) = G^R(\mathbf{x},\mathbf{x}_s)e^{-\eta^R|r-r_s|}\varepsilon_o{}^R(\mathbf{x},\omega) \tag{13a}$$
$$+ \int_V G^R(\mathbf{x},\mathbf{x}')e^{-\eta^R|r-r'|}\{\eta_s{}^{RR}E^R(\mathbf{x}',\omega) + \eta_s{}^{SR}E^S(\mathbf{x}',\omega)\}dV(\mathbf{x}')$$

$$E^S(\mathbf{x},\omega) = G^S(\mathbf{x},\mathbf{x}_s)e^{-\eta^S|r-r_s|}\varepsilon_o{}^S(\mathbf{x},\omega) \tag{13b}$$
$$+ \int_V G^S(\mathbf{x},\mathbf{x}')e^{-\eta^S|x-x'|}\{\eta_s{}^{RS}E^R(\mathbf{x}',\omega) + \eta_s{}^{SS}E^S(\mathbf{x}',\omega)\}dV(\mathbf{x}') \; .$$

Where,

$E^S(\mathbf{x},\omega)$: seismic energy carried by S wave per unit volume at $\mathbf{x}$;

η^R : total attenuation coefficient for Rayleigh wave, $\eta^R = \eta_i^R + \eta_s^{RR} + \eta_s^{SR}$;

η_s^{RR}: Rayleigh to Rayleigh waves scattering coefficient;

η_s^{SR} : S to Rayleigh waves scattering coefficient;

η^S : total attenuation coefficient for S wave, $\eta^S = \eta_i^S + \eta_s^{RS} + \eta_s^{SS}$;

η_i^S : absorption coefficient for S wave;

η_s^{RS} : Rayleigh to S waves scattering coefficient;

η_s^{SS} : S to S waves scattering coefficient;

$\varepsilon_0^S(\mathbf{x}_s,\omega)$: total S wave energy rate radiated from source divided by the velocity of S wave;

$G^R(\mathbf{x},\mathbf{x}')$: the geometrical spreading function for Rayleigh wave given by equation (7);

$G^S(\mathbf{x},\mathbf{x}')$: the geometrical spreading function for S wave in a half-space medium, and it can be approximated by

$$G^S(\mathbf{x},\mathbf{x}') = \frac{1}{4\pi|\mathbf{x}-\mathbf{x}'|} + \frac{1}{4\pi|\mathbf{x}-(\mathbf{x}')^*|} \; .$$

Where, $(\mathbf{x}')^*$ is the image point of $\mathbf{x}'$ with respect to the free surface z=0, i.e., $(\mathbf{x}')^*=(x', y',-z')$.

Equations (13a) and (13b) can be further simplified. Making a two-dimensional Fourier transform over the horizontal variable (x,y), equation can be reduced to,

$$\widetilde{E}^R(K,z,\omega) = \widetilde{G}^R(K,z;z_s;\omega)\varepsilon_0^R(\mathbf{x}_s,\omega) \tag{14a}$$
$$+ \int_0^{+\infty} \widetilde{G}^R(K,z;z';\omega)\{\eta_s^{RR}\widetilde{E}^R(K,z',\omega) + \eta_s{}^{SR}\widetilde{E}^S(K,z',\omega)\}dz' \; ,$$

$$\widetilde{E}^S(K,z,\omega) = \widetilde{G}^S(K,z;z_s;\omega)\varepsilon_0^S(\mathbf{x}_s,\omega) \tag{14b}$$

$$+\int_0^{+\infty} \tilde{G}^S(K,z;z';\omega)\{\eta_s^{RS}\tilde{E}^R(K,z;z';\omega) + \eta_s^{SS}\tilde{E}^S(K,z',\omega)\}dz' \ .$$

Where, K is the horizontal wave-number and

$$\tilde{G}^s(K,z;z';\omega)=\int_0^{+\infty} G(r,z;z';\omega)\exp(-\eta^s\sqrt{r^2+(z-z')^2}\,)J_o(Kr)rdr,$$

and

$$\tilde{G}^R(K,z;\omega)=g(z,\omega)\int_0^{+\infty} \exp(-\eta^R r)J_o(Kr)dr \ .$$

Solving the coupled equations (14a) and (14b), we can obtain the solution of energy transfer processes of S and Rayleigh waves. The time-history of total scattering energy can be determined by introducing proper time-delay phase factors to these coupled equations. Figure. (3) show the time history of total scattering energy of S and Rayleigh waves, for the case of η_i^S=0.01(km)$^{-1}$, η_s^{RS}=0.01(km)$^{-1}$, η_s^{SS}=0.02(km)$^{-1}$, η_i^R=0.03(km)$^{-1}$, η_s^{RR}=0.02(km)$^{-1}$ and η_s^{SR}= 0.01(km)$^{-1}$ for various source depths and center frequencies. Our results indicate that the shallower the source depth and the lower the frequency is, the contribution of scattered Rayleigh waves is larger. This is consistent with the observed results of Su and Aki (1991) as shown in Fig. 1, where earthquakes have an average focal depth of 8 km, whereas the average focal depth of quarry blasts is about 10m. Therefore, the latter contains much Rayleigh waves' contributions while the former dominated by S waves only. We also found that the contribution of Rayleigh waves decreases as the center frequency increasing. The suppressing of surface wave contribution, however, is not strong enough to directly fit the observed results shown in Fig. 1. This indicates strong attenuation of surface waves at higher frequencies due to absorption.

CONCLUSIONS AND FUTURE STUDIES

To date, we have developed the energy transfer theory for Rayleigh and S wave propagation in a random scattering and attenuation half-space medium. The solutions of our energy transfer equations can qualitatively explain the Su and Aki's observed results about the local earthquakes and quarry blasts (1991). Our study indicates that the surface wave scattering become important for the events with shallower focal depth, for instance, the quarry blasts and nuclear explosions. For the explosions at a regional distance, we expect similar conclusions. To solve such scattering problem at a regional distance we shall extend our energy transfer equations to more general cases. At the same time we shall calculate the coda Q_c^{-1} of the Chinese nuclear explosion and the nearby earthquakes by using the CDSN data. We expect that a similar discrimination between explosions and earthquakes as observed by Su and Aki for local events (1991) can be found in the events at regional distance, and our energy transfer theory can offer a physical basis.

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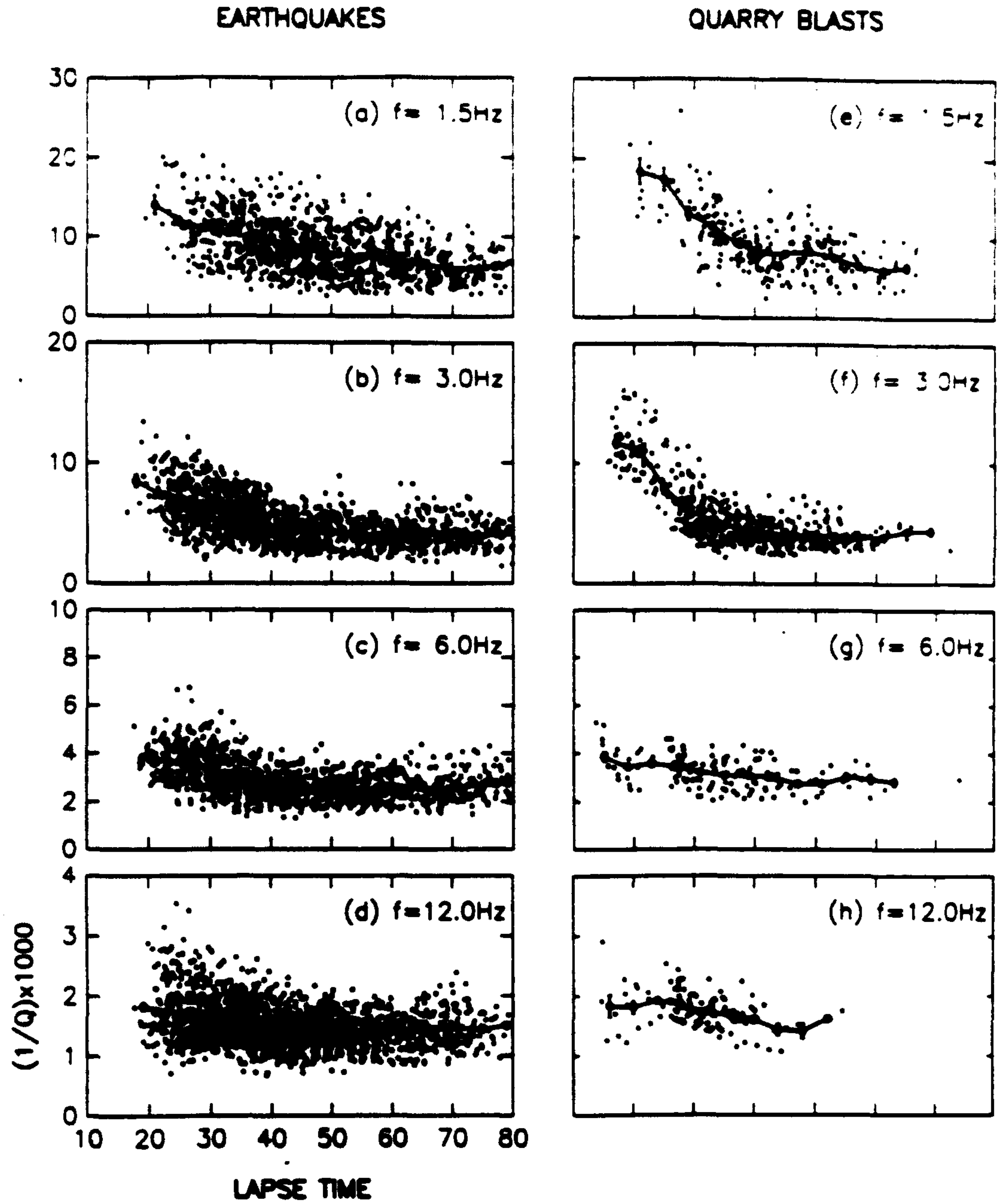

Figure 1. Coda Q^{-1} vs. lapse time obtained using the local earthquakes and quarry blasts in the south central Mojave Desert area. each open circle on the plot represents one measurement for a particular seismogram on a time window of 34 sec for frequency 1.5 Hz, 25Hz for 3 Hz, and 20sec for 6Hz and 12Hz. The solid line connects the mean points (solid circles) calculated by averaging the individual measurements in each 8 sec time interval with 4 sec overlapping at the adjacent mean points. The standard error of the mean is also shown for each mean point (from Su and Aki, 1991).

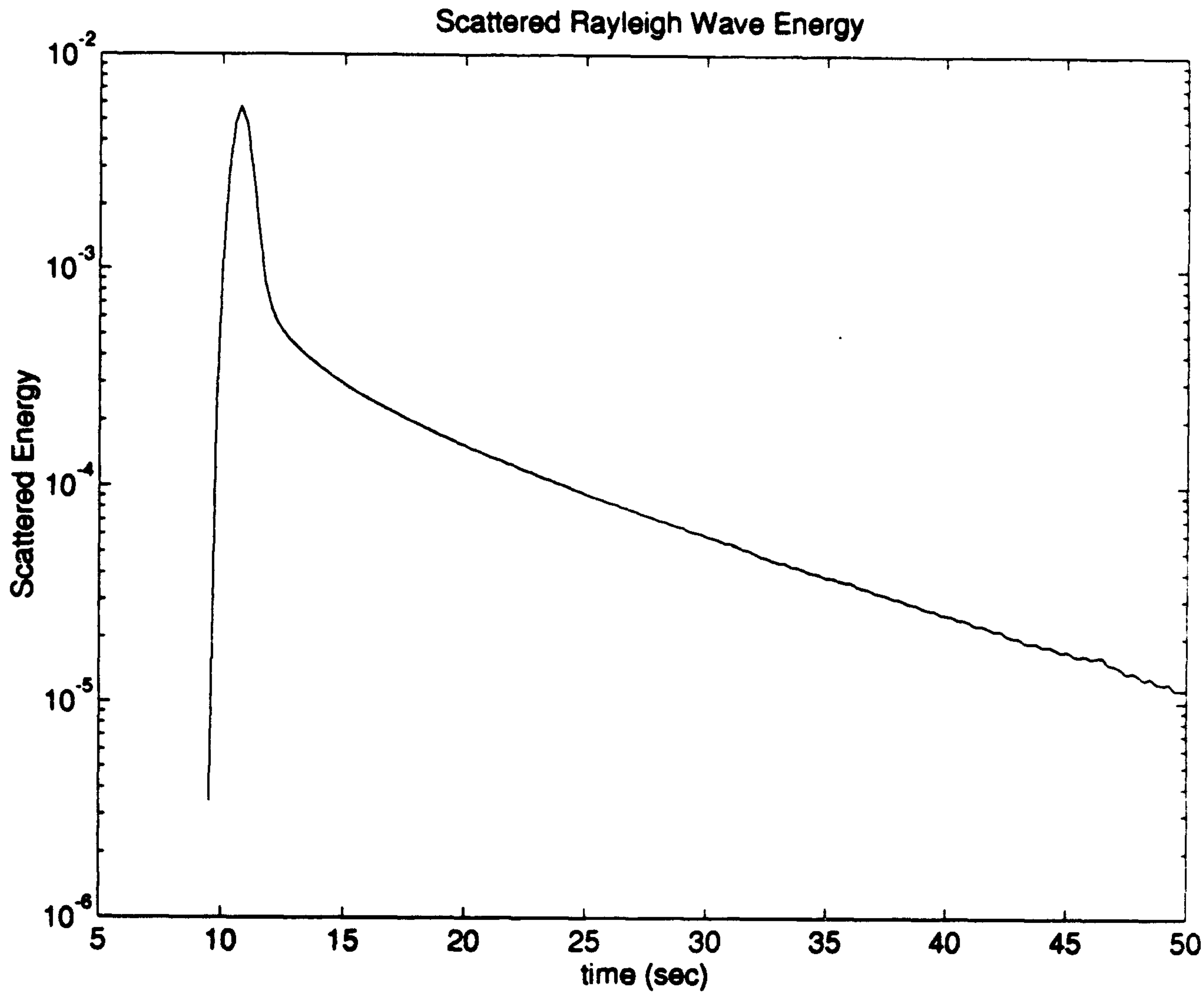

Figure 2. Scattered Rayleigh energy for the case of η_i^R=0.03(km)$^{-1}$, η_s^R=0.02(km)$^{-1}$ and ω=1Hz. Where r=30km and c_R=2.8km/sce.

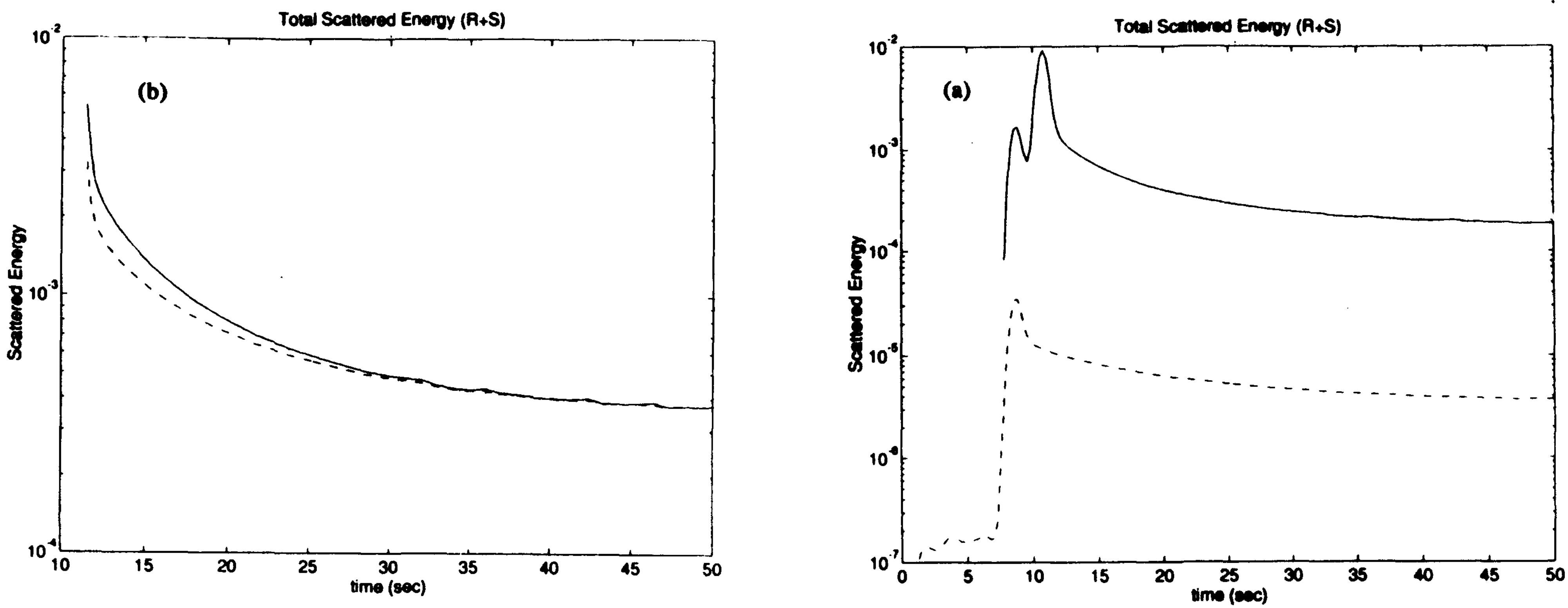

Figure 3. Focal depth and frequency w dependence of total scattered energy of Rayleigh and S waves, where η_i^R=0.03(km)$^{-1}$, η_s^{RR}=0.02(km)$^{-1}$, η_i^{SR}=0.01(km)$^{-1}$, η_i^S=0.01(km)$^{-1}$, η_s^{SS}=0.02(km)$^{-1}$, η_s^{RS}=0.01(km)$^{-1}$ and r=30km. (a). For the cases of zs=0.01km (solid line), zs=1km (dotted line) and zs=10km (dashed line). (b) For the cases of ω=1.5Hz (solid line) , ω=3.0Hz (dashed line) and ω=6Hz (dotted line).